Evolution of Bias in the Radio Population

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Outline

- Large-scale structure in the radio
- Cross-matching radio with optical surveys
- Angular correlation function
- Bias factor
- Future with SKA and LSST

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LSS with Radio

Observing large-scale cosmological structure requires knowledge of the most massive objects, over a large range of redshifts:

- Massive galaxies and clusters best trace the underlying dark matter structures.
- Distinguishing cosmological models requires large physical scales and sampling a large period of cosmic time.

Bias quantifies how a source population traces the dark matter and is an essential ingredient in observational cosmology

(more from Matt and Tzu-Ching this afternoon)

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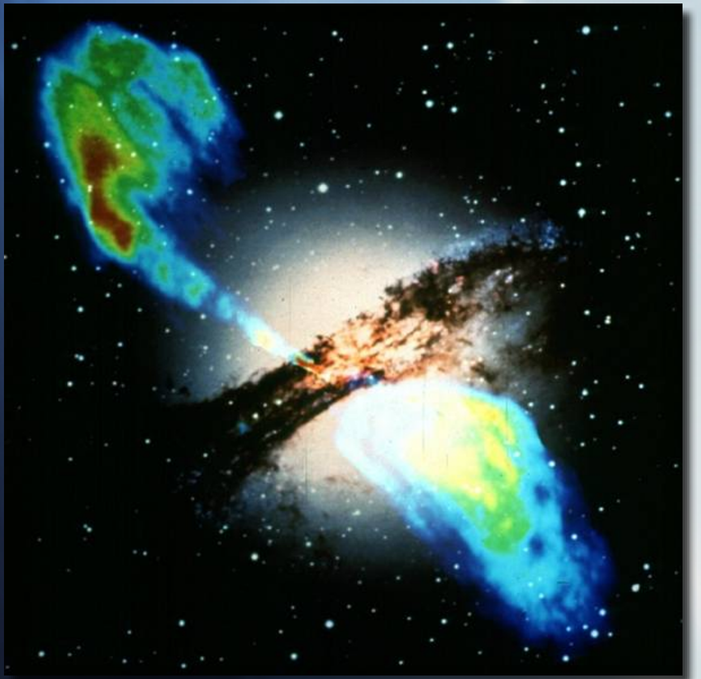
LSS with Radio



Radio surveys:

- ✓ Synchrotron emission from accretion by AGN
- ✓ ...or recent massive star-forming regions
- ✓ Unobscured by dust and our own atmosphere
- ✓ Probe high redshifts

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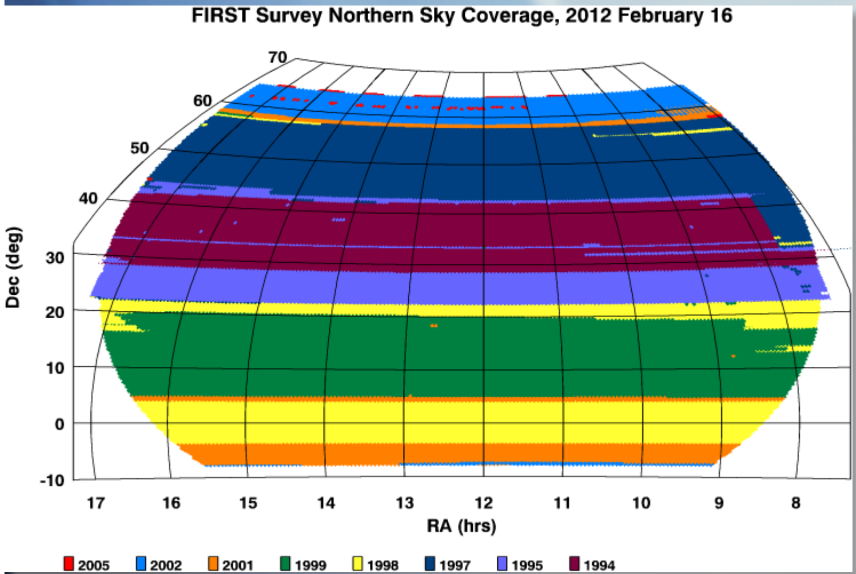
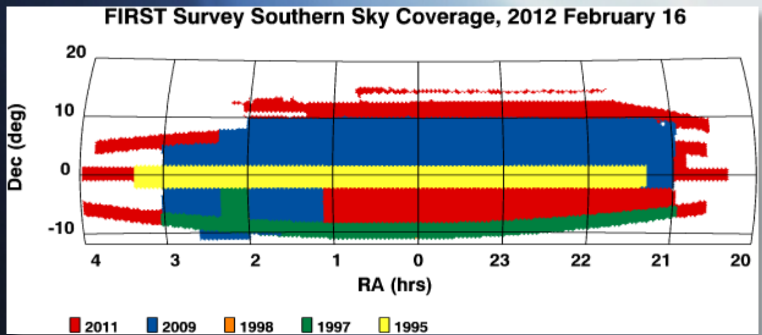
Radio Data

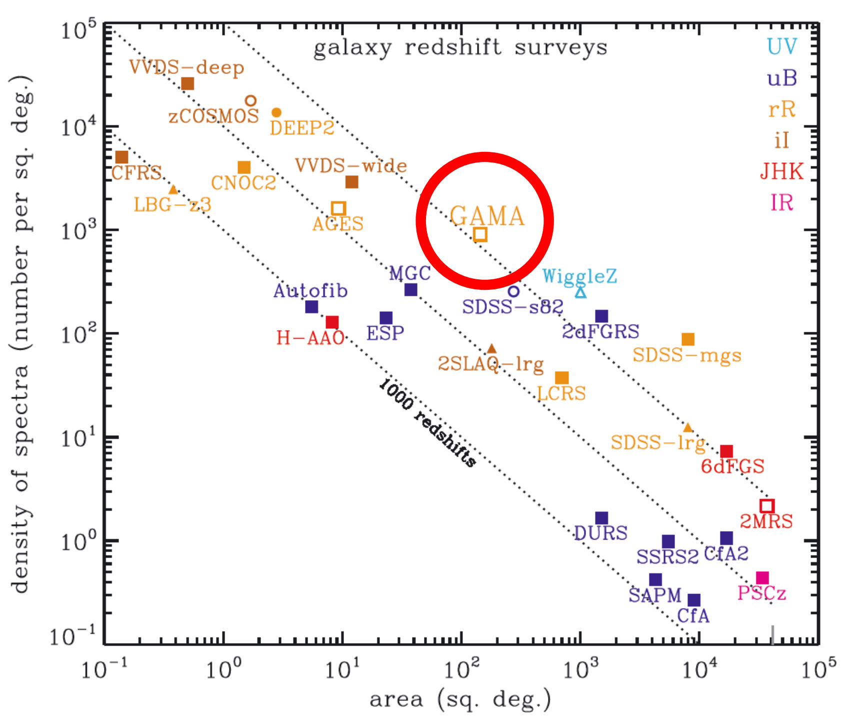




Faint Images of the Radio Sky at Twenty-cm (FIRST)

- 1.4 GHz VLA survey using B-configuration
- 5.4” resolution, 1 mJy detection limit
- >10,000 deg^2 sky coverage (~25%)
- ~950,000 sources

Optical/NIR Data



Baldry et al. (2010)

Galaxy And Mass Assembly (GAMA)

- 3.9m Anglo-Australian Telescope (AAT)
- Three equatorial fields (12 x 4 deg) centred on 9h, 12h and 14h30 covering 144 deg^2
- AAOmega spectrograph provides continuous spectra across two channels at 3720-8850Å with 3.5Å (blue) and 5.5Å (red) resolution
- 98% complete at r<19.4

→ ~140,000 spectroscopic redshifts

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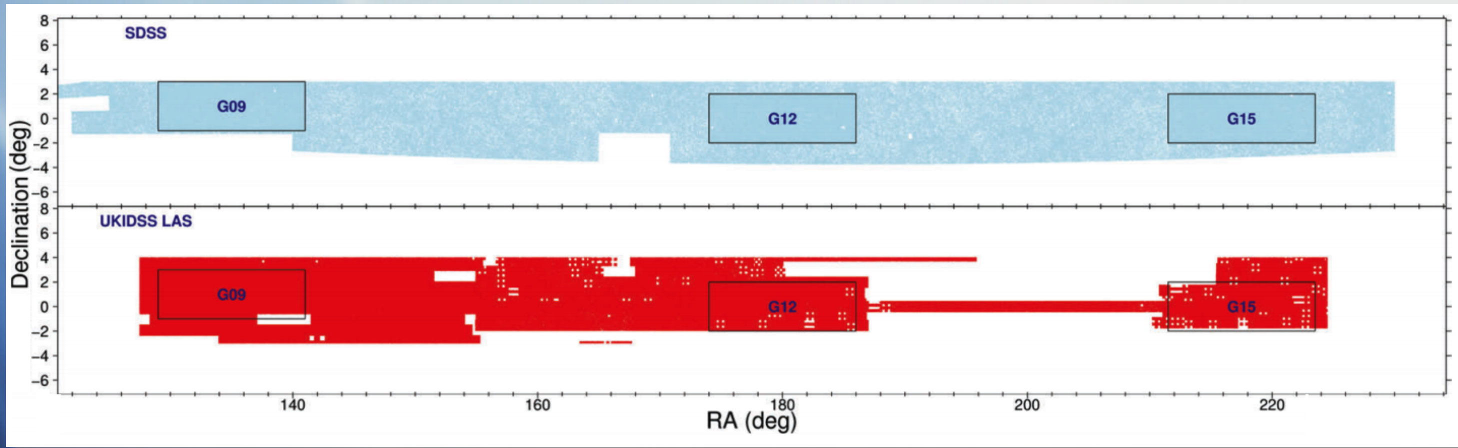
Optical/NIR Data

Sloan Digital Sky Survey (SDSS)

- 2.5m Sloan telescope @ Apache Point Observatory, New Mexico
- ~10,000 deg^2 in *ugriz* bands (r<22)



Hill et al. (2011)

UKIRT Infra-Red Deep Sky Survey (UKIDSS)
Large Area Survey (LAS)

- 3.8m UK Infra-Red Telescope (UKIRT) @ Mauna Kea, Hawaii
- ~2,000 deg^2 in *YJHK* bands

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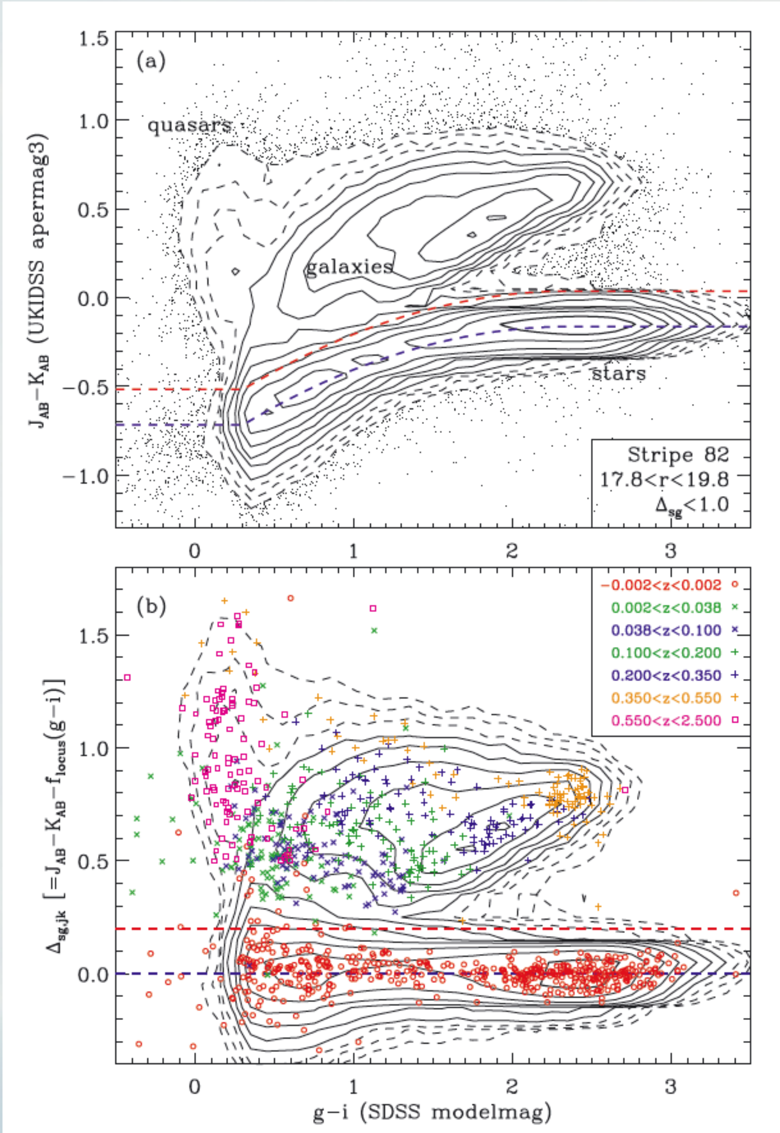
→ ~1,000,000 photometric redshifts per GAMA field

Cross-matching

Star-galaxy separation reduces the size of the catalogue by ~50% and improves reliability of subsequent matches to the radio positions.

Use *J-K* and *g-i* colours to distinguish galaxies and quasars from the stellar locus in the optical catalogue (Baldry+2010).



Baldry et al. (2010)

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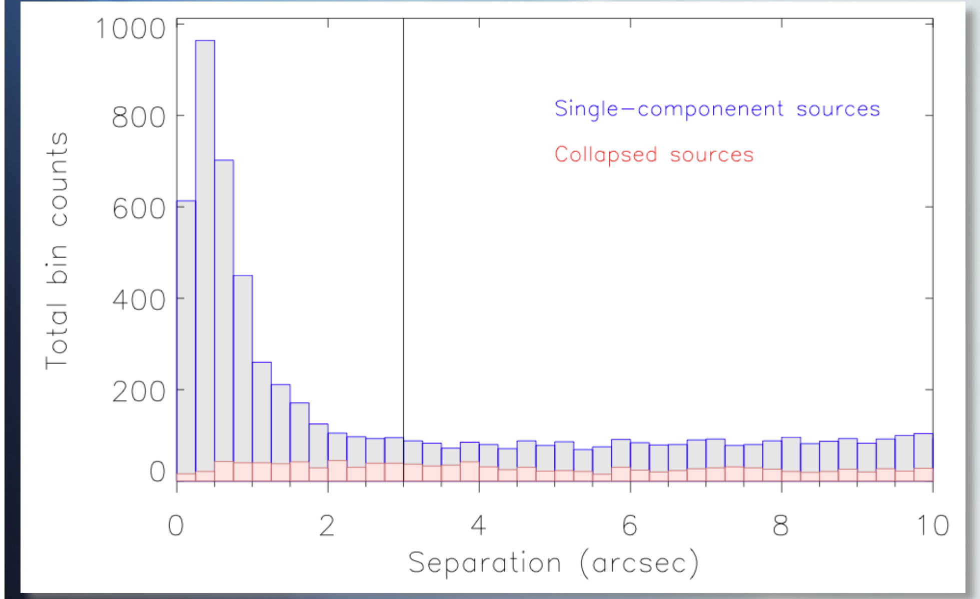
Cross-matching



Nearest neighbour match between radio and optical catalogues with 3 arcsec cut-off (~4% of matches occur by chance)

~14,000 radio sources → 3,886 matches

- 1,424 with spectroscopic redshifts
- 422 collapsed radio sources
- ~156 spurious matches

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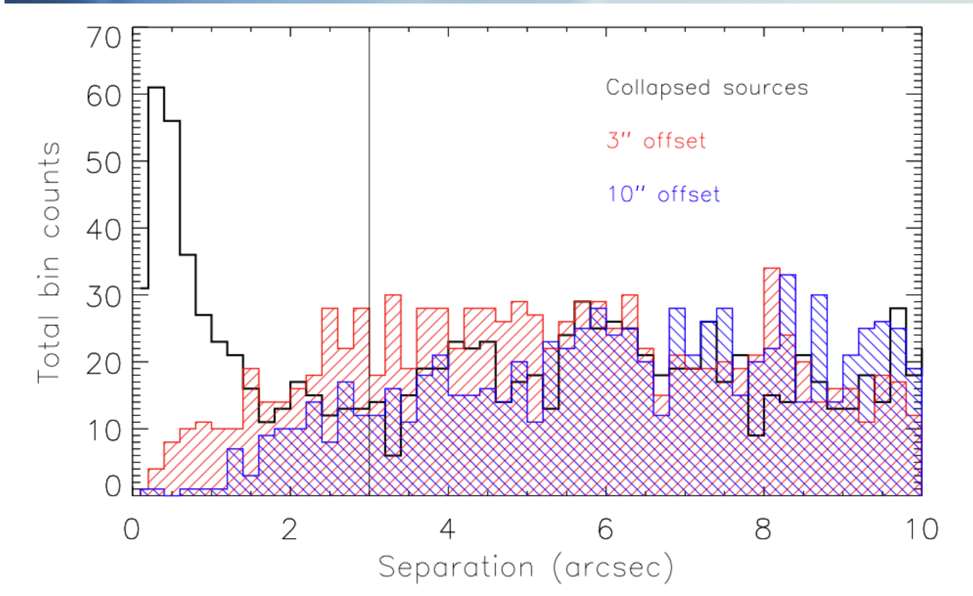
Cross-matching



Does the collapsing procedure reliably locate the host galaxy position?

Randomly shift expected positions of radio galaxy cores by 3" and 10" and repeat nearest neighbour match with optical catalogue.

→ Majority of <3" matches appear not to be coincidental.

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Angular Correlation Function

-*"The excess probability of finding a galaxy at an angular distance θ from another galaxy, as compared with a Poissonian (unclustered) distribution"*

Source pairs are measured and binned by angular separation θ using observed sources (D) and those from a random mock catalogue (R), and the correlation function given by:

$$w(\theta) = \frac{DD - 2DR + RR}{RR}$$

where DD and RR correspond to galaxy-galaxy pairs within the data and random catalogues and DR corresponds to the cross-pair counts between catalogues.

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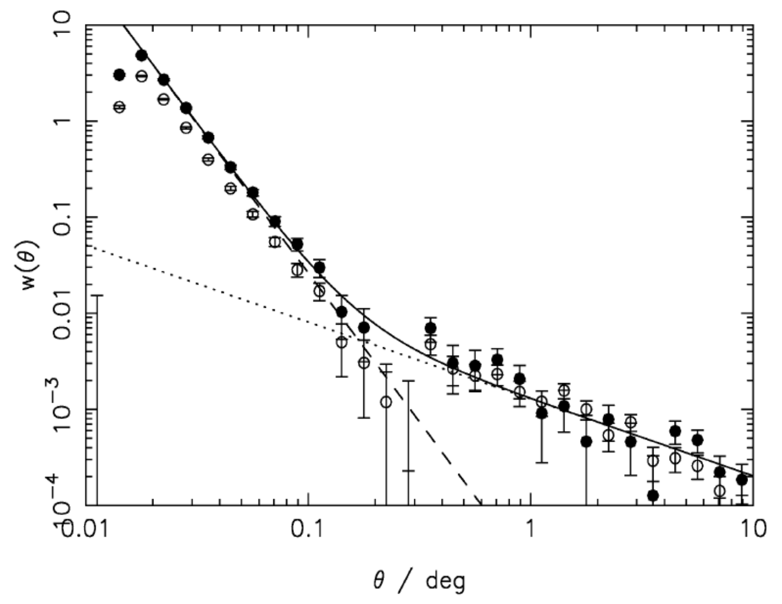
Angular Correlation Function

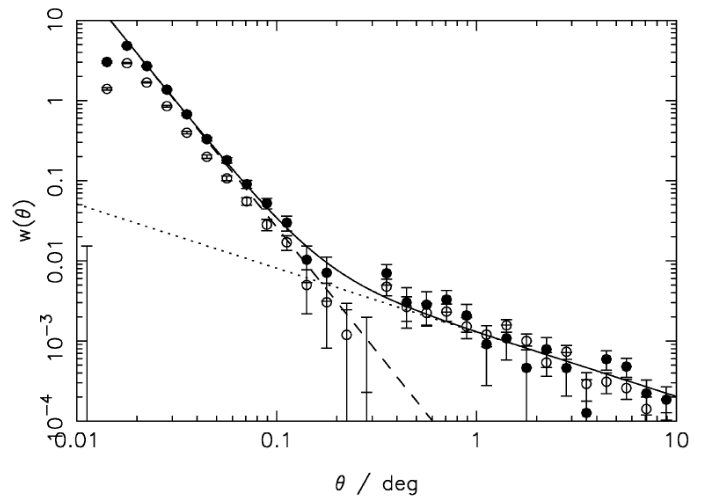


Blake & Wall (2002b)

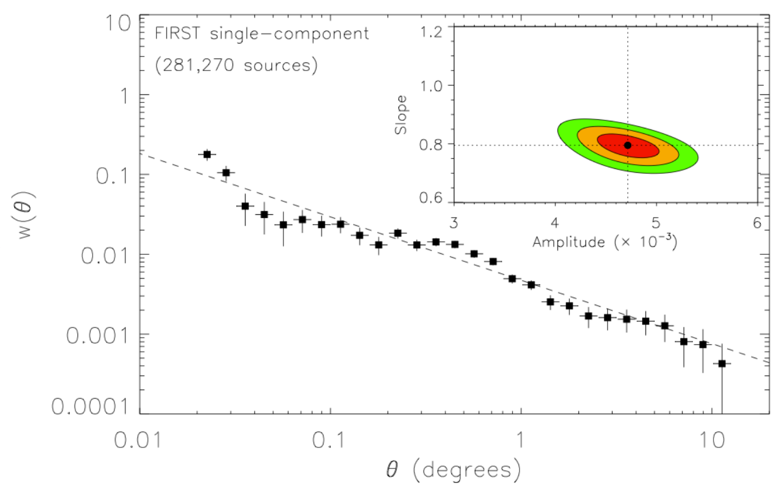
Radio source ACF fitted with a double power law function:

- $\theta > \sim 10'$: Large-scale gravitational clustering. Slope of ~0.8, similar to that found from surveys at other wavelengths.
- $\theta < \sim 10'$: Excess small-scale pairs due to size distribution of multiple-component radio sources (AGN + lobes)

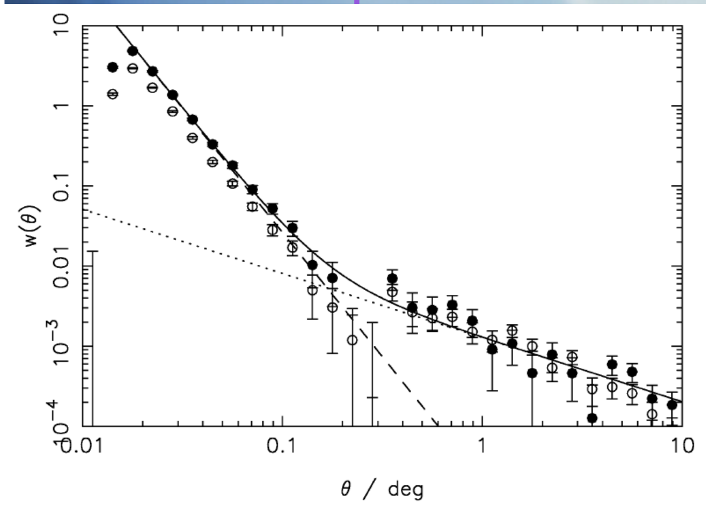
Angular Correlation Function



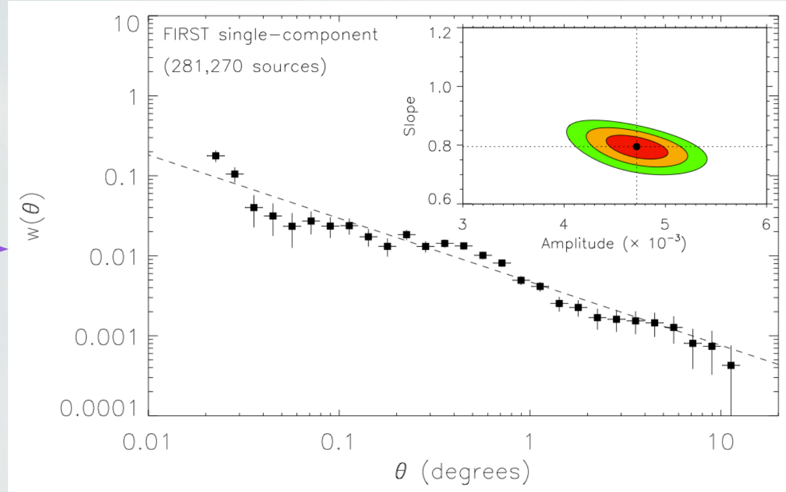
Blake & Wall (2002b)



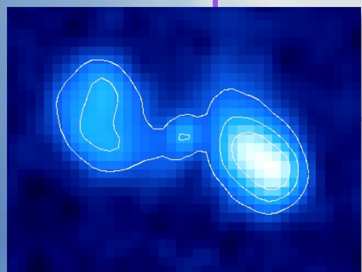
Angular Correlation Function

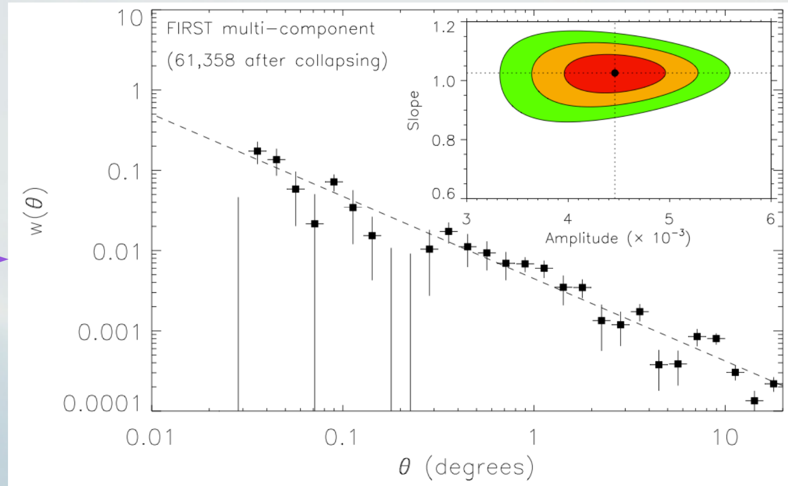


Blake & Wall (2002b)



Collapse groups of sources within 72”





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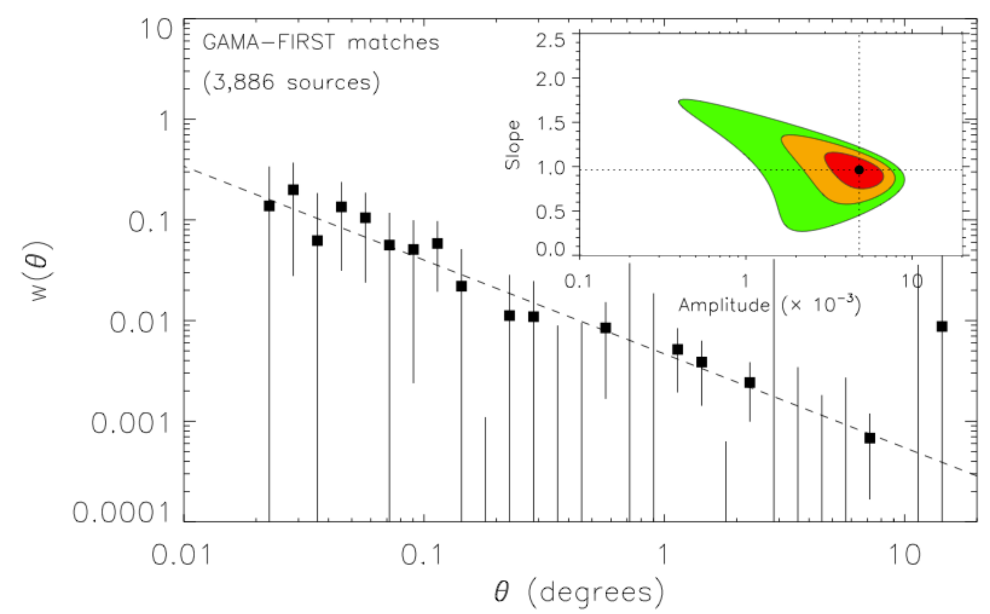
Angular Correlation Function

Cross-matched sources @ z~0.5



68%
95%
99%

A = 0.0047 ± 0.0012 (Amplitude)

γ - 1 = 0.93 ± 0.13 (Slope)

Slope greater than the canonical value of 0.8 found in optical studies (but only by 1σ). Often a fixed parameter to facilitate fitting A, or a double power-law.

Bias

$$b(z) = \sqrt{\frac{\xi_{\mathrm{gal}}(8, z)}{\xi_{\mathrm{DM}}(8, z)}}$$

$b > 1$: More strongly clustered than dark matter

$b < 1$: Less strongly clustered than dark matter

Calculated as a function of the correlation length, r_0 (in h^{-1}Mpc) and growth factor *D(z)* :

$$b(z) = \left[\frac{r_0(z)}{8}\right]^{\gamma/2} \frac{J_2^{1/2}}{\sigma_8 D(z)/D(0)}$$

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Bias

Limber inversion:

$$A = r_0^{\gamma} H_{\gamma} \left(\frac{H_0}{c}\right) \frac{\int_0^{\infty} N^2(z)(1+z)^{\gamma-(3+\epsilon)} \chi^{1-\gamma}(z) E(z) dz}{\left[\int_0^{\infty} N(z) dz\right]^2}$$

Take angular clustering parameters (A, γ) and a redshift distribution to determine the spatial clustering scale, r_0

…under certain assumptions about the clustering evolution:

$$\epsilon = \begin{cases} \gamma - 1 & \text{linear} \\ \gamma - 3 & \text{comoving} \\ 0 & \text{stable} \end{cases}$$

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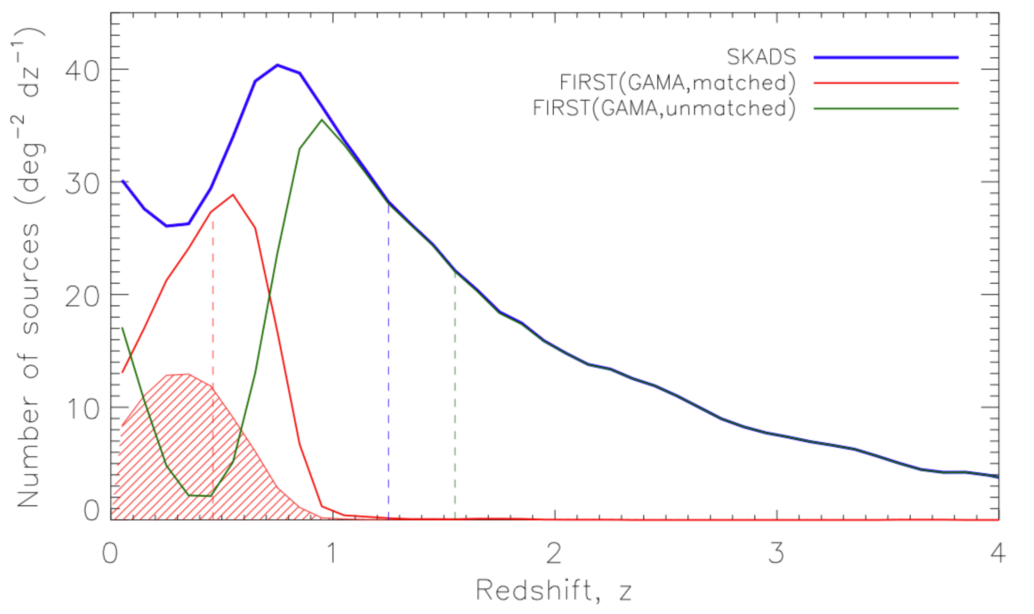
Bias

SKADS Simulated Skies (S^3; Wilman et al. 2008) provides a simulated radio catalogue which we can cut at 1 mJy to roughly emulate the expected redshift distribution of FIRST radio sources.



FIRST sources with GAMA/SDSS optical identifications have associated redshifts, giving a directly observed redshift distribution.

By assuming the SKADS distribution for FIRST, we subtract the observed redshift distribution for the matched sources to obtain one for those remaining sources without optical IDs.

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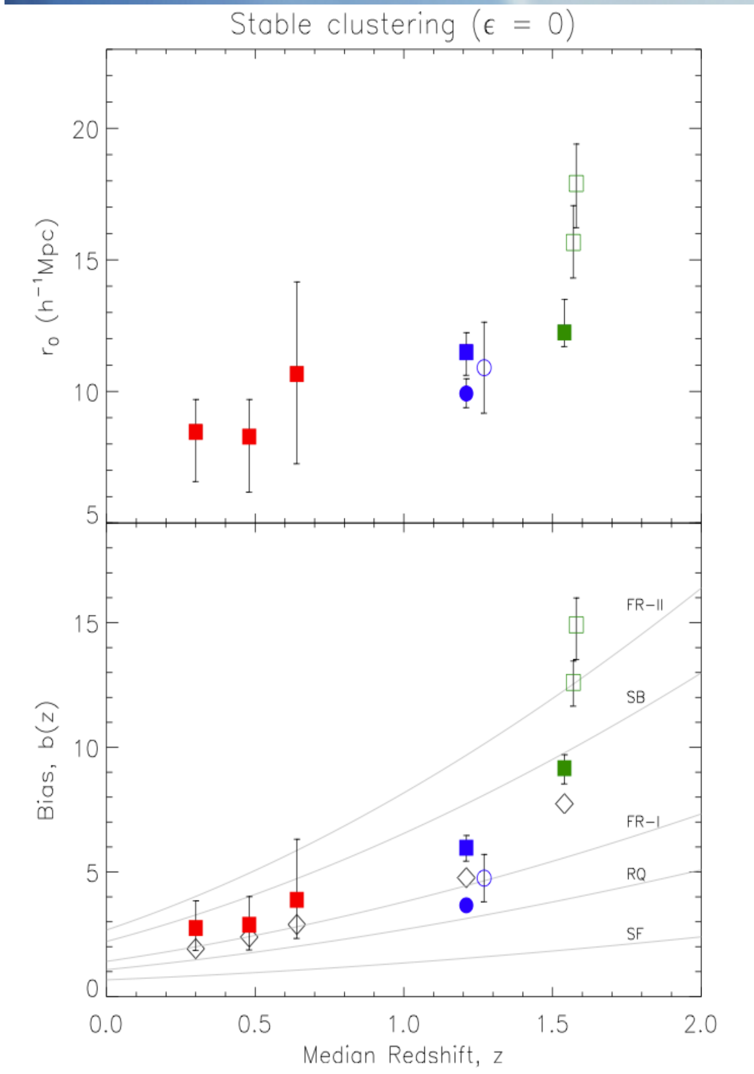
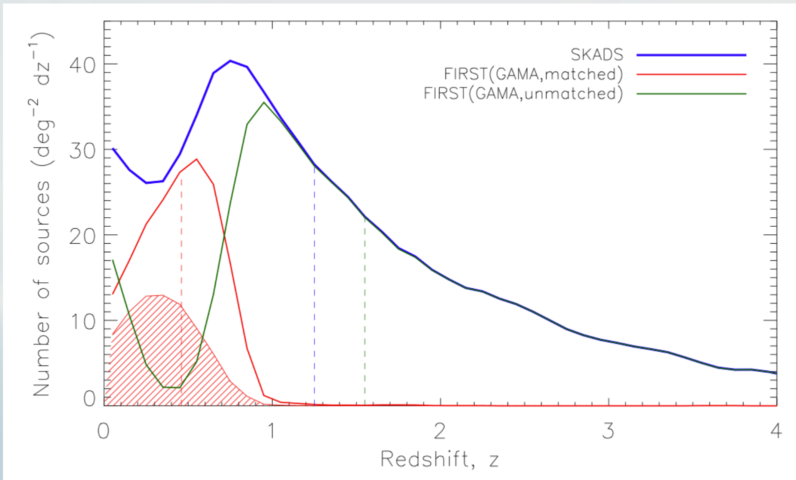
Bias



We measure clustering scale and bias across a range of z~0.3 to z~1.5 (with some more reliable than others), with a trend of clustering being stronger at higher redshift where we observe the more massive AGN-driven radio sources.



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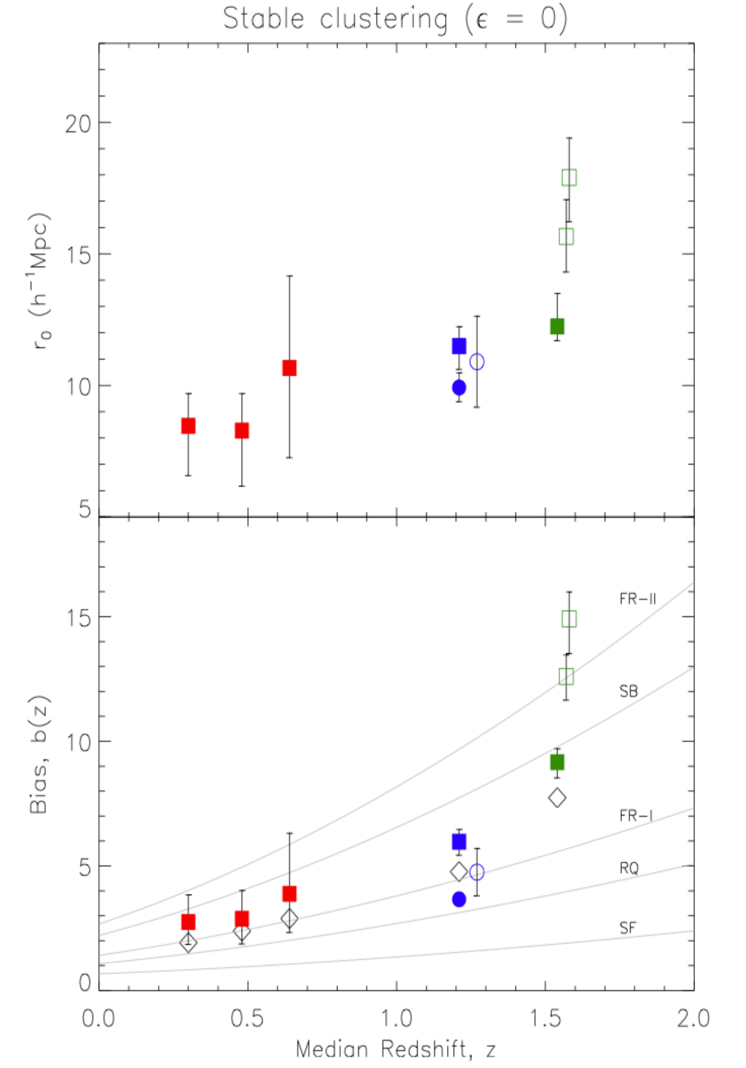
Bias



How do we fill in the gaps?

To reduce error bars and bin our matched samples into smaller redshift slices over a larger range, we need a bigger sample!

BUT, bigger does not necessarily mean deeper!

Below ~0.1 mJy, radio catalogues become dominated by nearby star-forming galaxies rather than the larger, more distant AGN we are interested in for cosmology. These are the sources for which we do not have optical IDs:

Need redshifts for optically-faint, radio-loud galaxies → *deeper optical surveys*

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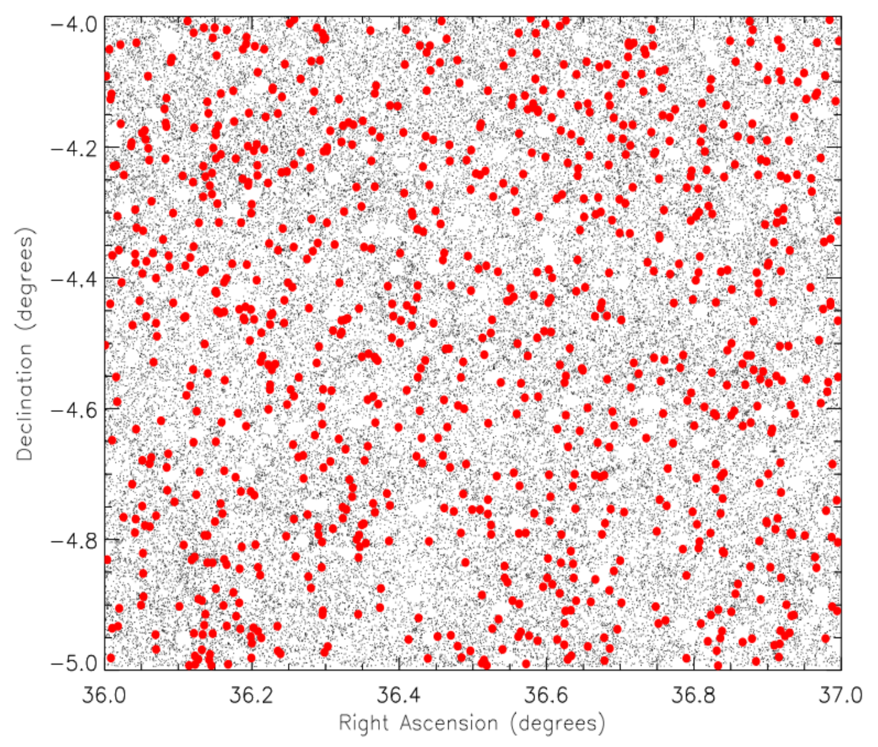
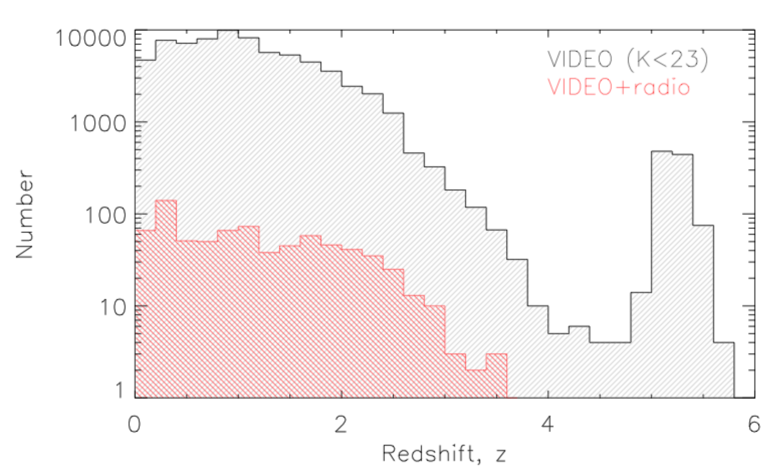
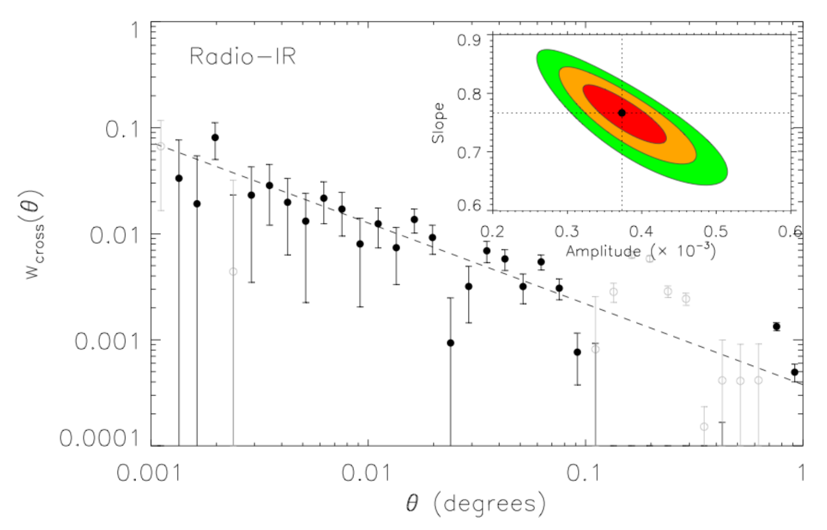
...Narrow & Deep (VIDEO)

1 x 1 deg @ K<23, $S_{1.4}$>90 μJy

→ 900 radio sources + redshifts







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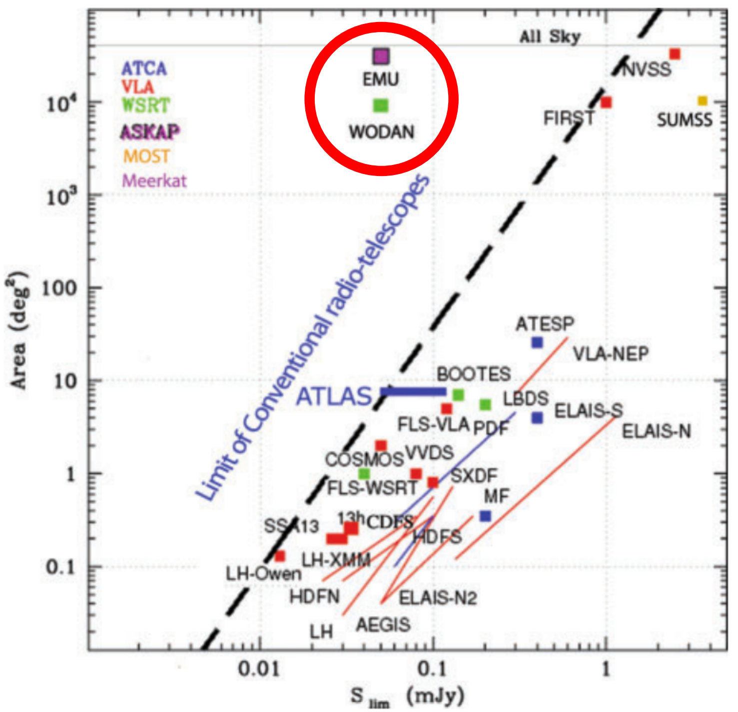
Future Surveys



Norris et al. (2011)

FIRST → SKA (+ precursors)

- EMU (Norris+2011) with ASKAP telescope
- WODAN (Röttgering+12) with WSRT

Full sky coverage, 20x deeper than FIRST (50 μJy)
10” (EMU) / 15” (WODAN) resolution
~ 30,000,000 sources

- LOFAR (Röttgering+10)

GAMA/SDSS → LSST

- ~5 mag deeper photometry
- Additional *y*-band coverage
- ~4 billion redshifts

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Summary

- FIRST radio data + GAMA/SDSS redshifts
    - → Direct bias calculation up to z~0.6
- Subtract N(z) from simulated 1 mJy distribution
    - → Extend b(z) measure to z~1.5 for sources without optical IDs
- Similar success with narrower, deep fields in VIDEO

Future:

- More photo-z's from wider, deeper optical surveys
- Greater cross-matching success
- Better statistics for finer redshift binning of b(z)

Thanks for listening!

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